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MULTIPATH IN THE THREE-DIMENSIONAL UNDERWATER ARRAY.(U)
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MULTIPATH IN THE THREE-DIMENSIONAL UNDERWATER ARRAY

A planar array of widely dispersed hydrophones deployed in a horizontal plane several hundred meters below the surface of the sea ~~has been~~ analyzed. and reported earlier [1, 2]. Because of the dispersive nature of the underwater medium, signal energy approaches the array from a source along a number of refracting paths. This results in multipath interference and a possible consequent loss of output. Ray arrivals from the source typically fall into a range of vertical angles at the receiver which are $\pm$ 10° relative to the horizontal. The vertical beamwidth of a planar antenna is large enough to accept all rays in such a range, hence it is multipath sensitive. A three-dimensional array is capable of a sharper vertical focus and will be less sensitive to the kind of multipath typical in this application. In fact, by suitably processing the array output there is the possibility that the multipath arrivals can be separately received and then combined in phase to achieve an "angle of arrival diversity" system, as suggested in Figure 3.1. Such systems have been proposed for tropospheric scatter receivers.

We analyze the mean properties of such a system below. If the array is focused to look in the y-z plane its response to a signal at angle ϕ relative to the x-z plane is

[1] Fred Haber, "Mean Array Gain Pattern of a Floating Acoustic Array in a Non-Transparent Medium," VFRC QPR No. 26, August 1978, pp. 42-44.
[2] Fred Haber, "Variance of the Power Gain of the Floating Array," VFRC QPR No. 28, February 1979, pp. 24-29.

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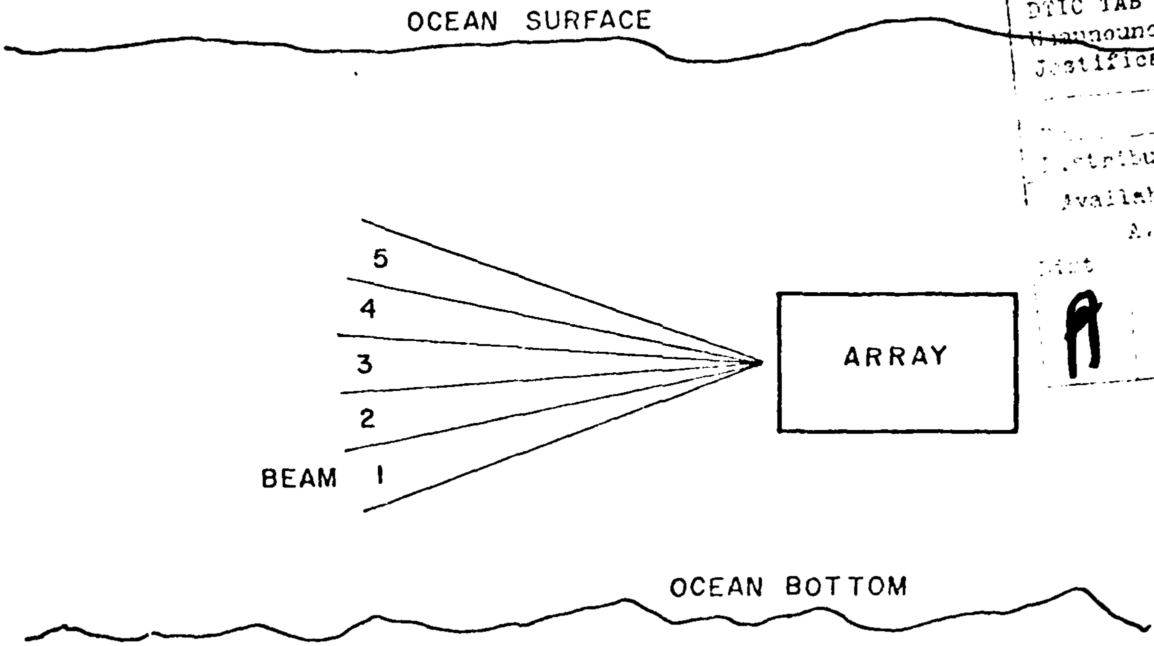

FIGURE 3.1 MULTIPLE VERTICAL BEAMS FOR MULTIPATH RESOLUTION

$$A(\phi,\theta_s) = \sum_{m=1}^{M}\sum_{n=1}^{N} B_m e^{j\{k[x_n\sin\theta_m\cos\phi + y_n(\sin\theta_m\sin\phi - \sin\theta_s) + z_n(\cos\theta_m - \cos\theta_s)] + \phi_m\}} \qquad (1)$$

Here θ_s is the vertical angle to which the array is to be focused; (x_n, y_n, z_n) is the position of the nth array element. (1) assumes M ray arrivals each given by $B_m e^{j\phi_m}$ with vertical arrival angle θ_m.

We concentrate on the output when the source is on the main beam; that is, when $\phi = 90°$. Then

$$A(\tfrac{\pi}{2},\theta_s) = \sum_{m=1}^{M}\sum_{n=1}^{N} B_m e^{j\{k[y_n(\sin\theta_m - \sin\theta_s) + z_n(\cos\theta_m - \cos\theta_s)] + \phi_m\}} \qquad (2)$$

We calculate the mean power response of the array given by

$$\left\langle \left| A^2\left(\frac{\pi}{2}, \theta_s\right) \right| \right\rangle = \sum_{m_1}^{M} \sum_{m_2}^{M} \sum_{n_1}^{N} \sum_{n_2}^{N} \left\langle B_{m_1} B_{m_2} \right\rangle$$

$$\cdot \left\langle e^{jk[y_{n_1}(\sin\theta_{m_1} - \sin\theta_s) - y_{n_2}(\sin\theta_{m_2} - \sin\theta_s)]} \right.$$

$$\left. \cdot\, e^{jk[z_{n_1}(\cos\theta_{m_1} - \cos\theta_s) - z_{n_2}(\cos\theta_{m_2} - \cos\theta_s)]} \right\rangle$$

$$\cdot \left\langle e^{j(\phi_{m_1} - \phi_{m_2})} \right\rangle \tag{3}$$

We have

$$\left\langle e^{j(\phi_{m_1} - \phi_{m_2})} \right\rangle = \delta_{m_1 m_2} \quad , \tag{4}$$

the Kronecker delta, so that

$$\left\langle \left| A^2\left(\frac{\pi}{2}, \theta_s\right) \right| \right\rangle = \sum_{m=1}^{M} \sum_{n_1=1}^{N} \sum_{n_2=1}^{N} \left\langle B_m^{\,2} \right\rangle \left\langle e^{jk(y_{n_1} - y_{n_2})(\sin\theta_m - \sin\theta_s)} \right.$$

$$\left. \cdot\, e^{jk(z_{n_1} - z_{n_2})(\cos\theta_m - \cos\theta_s)} \right\rangle$$

$$= \sum_{m=1}^{M} \left\langle B_m^{\,2} \right\rangle \left[N + \sum_{\substack{n_1=1 \\ n_1 \neq n_2}}^{N} \sum_{n_2=1}^{N} \left\langle e^{jk\, y_{n_1}(\sin\theta_m - \sin\theta_s)} \cdot e^{jk\, z_{n_1}(\cos\theta_m - \cos\theta_s)} \right\rangle \right.$$

$$\left. \cdot \left\langle e^{-jky_{n_2}(\sin\theta_m - \sin\theta_s)} \cdot e^{-jkz_{n_2}(\cos\theta_m - \cos\theta_s)} \right\rangle \right] \tag{5}$$

We assume all vectors (y_{n_i}, z_{n_i}), $n_i = 1, 2, \ldots N$ identically distributed. Furthermore, the random variables y_{n_i} and z_{n_i} are assumed independent and symmetrical around the origin. Then

$$\left\langle \left| A^2\left(\frac{\pi}{2}, \theta_s\right) \right| \right\rangle = \sum_{m=1}^{M} \left\langle B_m^{\,2} \right\rangle \left[N + (N^2 - N) \cdot \left\langle e^{jky_n(\sin\theta_m - \sin\theta_s)} \right\rangle^2 \cdot \left\langle e^{jkz_n(\cos\theta_m - \cos\theta_s)} \right\rangle^2 \right] \tag{6}$$

The expectations on the right are characteristic functions,

$$\phi(jt) = \left\langle e^{jtu} \right\rangle \tag{7}$$

where the random variable u is either y_n or z_n and t is correspondingly either $k(\sin\theta_m - \sin\theta_s)$ or $k(\cos\theta_m - \cos\theta_s)$. The random variables will here be specified as, either, uniformly distributed in an interval (-h, h), or normally distributed around zero with variance σ^2. Thus for the uniform case

$$\phi(jt) = \frac{\sin ht}{ht} \tag{8}$$

and for the normal case

$$\phi(jt) = e^{-\frac{1}{2}\sigma^2 t^2} \tag{9}$$

If the variables y_n and z_n are both normal with variance σ_y^2 and σ_z^2, respectively, we have

$$\left\langle \left| A^2\left(\frac{\pi}{2},\theta_s\right)\right| \right\rangle = \sum_{m=1}^{M} \left\langle B_m^{\;2} \right\rangle N \left\{ 1 + (N-1) \cdot \right. \tag{10}$$

$$\left. \cdot\, e^{-[\sigma_y^{\;2} k^2 (\sin\theta_m - \sin\theta_s)^2 + \sigma_z^{\;2} k^2 (\cos\theta_m - \cos\theta_s)^2]} \right\}$$

If the variable y_n is normal with variance σ_y^2 and the variable z_n is uniform in (-h, h) then

$$\left\langle \left| A^2\left(\frac{\pi}{2},\theta_s\right)\right| \right\rangle = \sum \left\langle B_m^{\;2} \right\rangle N \left\{ 1 + (N-1)\, e^{-\sigma_y^{\;2} k^2 (\sin\theta_m - \sin\theta_s)^2} \right. \tag{11}$$

$$\left. \cdot \left[\frac{\sin kh(\cos\theta_m - \cos\theta_s)}{kh(\cos\theta_m - \cos\theta_s)} \right]^2 \right\}$$

An inspection of (10) or (11) leads to the conclusion that if the vertical dimension of the array is in the order of 10 wavelengths the vertical beamwidth will be about ± 1°. Furthermore rays entering through this narrow beamwidth (hence excluding other rays arriving at vertical angles outside the vertical beamwidth) will be sufficiently compact to avoid the effect of phase decorrelation across the array.

We are therefore led to propose the following concept. Let the array simultaneously form contiguous vertical beams as indicated in Figure 3.1. Outputs corresponding to each beam will be simultaneously present. These outputs are then coherently combined. The operations required are as indicated in Figure 3.2. The mechanism being suggested is similar to that used in angle of arrival diversity communication systems with maximal ratio combining of the diversity signals. As a rule in these systems each diversity branch has a separate directive sensor and preamplifier. Here sensors and preamplifiers are common for all branches.

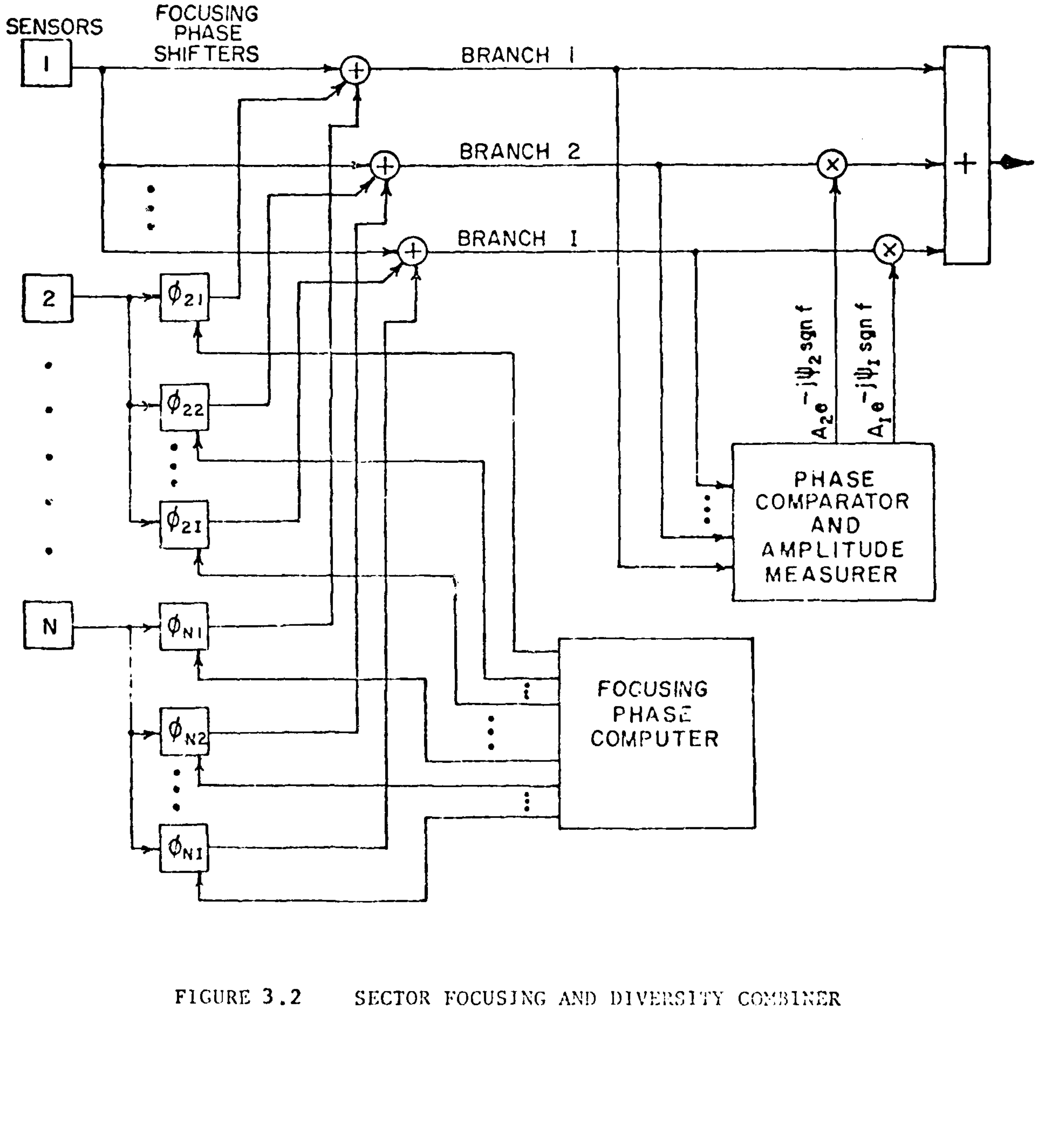

FIGURE 3.2 SECTOR FOCUSING AND DIVERSITY COMBINER

Because sensors are common one may question the effect of noise generated at the sensor or preamplifier input. Will such noise be independent when observed at the point of combination of the diversity branches? The following is a discussion of that point.

A filter

$$H(f) = A(f)\ e^{j\phi(f)}$$

which acts as a constant gain device and constant phase shifter - that is, with

$$A(f) = A$$

$$\phi(f) = -\phi\ \mathrm{sgn}\ f \qquad (\phi \text{ a constant})$$

can be represented by

$$H(f) = A\ e^{-j\phi\,\mathrm{sgn}\ f} = A\cos(-\phi\ \mathrm{sgn}\ f) + j\,A\sin(-\phi\ \mathrm{sgn}\ f)$$

$$= A\cos\phi - j\,A\sin\phi\ \mathrm{sgn}\ f$$

A filter with frequency characteristic

$$H_h(f) = -j\ \mathrm{sgn}\ f$$

is a Hilbert transforming filter so that a wave function n(t) applied to H(f) as defined above emerges as

$$n_o(t) = A\cos\phi\ n(t) + A\sin\phi\ \hat{n}(t)$$

where $\hat{n}(t)$ is the Hilbert Transform of n(t).

By direct application of the definitions and by use of the statistical properties of the Hilbert Transform one can show that for stationary, zero mean, processes,

$$\left\langle n_o(t+\tau)\, n_o(t)\right\rangle = A^2 \left\langle n(t+\tau)\, n(t)\right\rangle = A^2 R_n(\tau)$$

Input and output autocorrelation functions are proportional. $R_n(\tau)$ is the input autocorrelation function. Also,

$$\left\langle n_o(t+\tau)\, n(\tau)\right\rangle = A \cos\phi\, R_n(\tau) + A \sin\phi\, \hat{R}_n(\tau) \ ,$$

giving a relationship between input-output cross-correlation function and the input autocorrelation function. $\hat{R}_n(t)$ is the Hilbert Transform of $R_n(t)$. Finally for an input n(t) applied to separate filters

$$H_1(f) = A_1\, e^{-j\phi_1 \operatorname{sgn} f} \qquad \text{and} \qquad H_2(f) = A_2\, e^{-j\phi_2 \operatorname{sgn} f}$$

the cross-correlation function of the two outputs $n_{o_1}(t)$ and $n_{o_2}(t)$ is

$$\left\langle n_{o_1}(t+\tau)\, n_{o_2}(t)\right\rangle = A_1A_2[\cos(\phi_1-\phi_2)\, R_n(\tau) + \sin(\phi_1-\phi_2)\, \hat{R}_n(\tau)]$$

Consider now the block diagram of Figure 3.2. Each branch is comprised of the sum of N inputs, one from each array element and phase shifter. Branch 1, for instance, contains a wave function

$$N_1(t) = \sum_{n=1}^{N} n_{on1}(t) = \sum_{n=1}^{N} [\cos\phi_{n1} n_n(t) + \sin\phi_{n1}\, \hat{n}_n(t)]$$

where $n_n(t)$ is the output at the n'th sensor, and $n_{on1}(t)$ is the phase-shifted output of the n'th sensor contributing to branch 1. ϕ_{n1} is defined in Figure 3.2.

The output $N_1(t)$ will ultimately be applied through the second filter with characteristic given by $A_1 e^{-j\psi_1 \operatorname{sgn} f}$ resulting in an output

$$M_1(t) = A_1 \sum_{n=1}^{N} [\cos(\phi_{n1} + \psi_1)\, n_n(t) + \sin(\phi_{n1} + \psi_1)\, \hat{n}_n(t)]$$

For all I branches taken together we get

$$N(t) = \sum_{i=1}^{I} M_i(t) = \sum_{i=1}^{I} \sum_{n=1}^{N} A_i [\cos(\phi_{ni} + \psi_i) n_n(t) + \sin(\phi_{ni} + \psi_i)\, \hat{n}_n(t)]$$

We view the $n_n(t)$ to be Gaussian noise, present at the sensor outputs – generated in the sensor, its preamplifier and the sensor's immediate surroundings. We assume $n_n(t)$ is independent of $n_m(t)$ for $n \neq m$. Thus we exclude external noise which may be correlated across several sensors The variance of $N(t)$ is then

$$\left\langle N^2(t) \right\rangle = \sum_{i=1}^{I} \sum_{j=1}^{I} \sum_{n=1}^{N} \sum_{m=1}^{N} \Big\langle A_i A_j [\cos(\phi_{ni} + \psi_i) n_n(t) + \sin(\phi_{ni} + \psi_i)\, \hat{n}_n(t)] \cdot [\cos(\phi_{mj} + \psi_j) n_m(t) + \sin(\phi_{mj} + \psi_j) \hat{n}_m(t)] \Big\rangle$$

$$= \sum_{i=1}^{I} \sum_{j=1}^{I} \sum_{n=1}^{N} \Big[\left\langle A_i A_j \cos(\phi_{ni} + \psi_i) \cos(\phi_{nj} + \psi_j) \right\rangle \left\langle n_n^2(t) \right\rangle + \left\langle A_i A_j \sin(\phi_{ni} + \psi_i) \sin(\phi_{nj} + \psi_j) \right\rangle \left\langle \hat{n}_n(t) \right\rangle \Big]$$

We have used the independence condition [illegible] the independence

[illegible]

of $n_n(t)$ and $\hat{n}_m(t)$ for all n and m for a Gaussian process. It can be shown that

$$\left\langle n_n^2(t) \right\rangle = \left\langle \hat{n}_n^2(t) \right\rangle$$

so that

$$\left\langle N^2(t) \right\rangle = \sum_{n=1}^{N} \left\langle n_n^2(t) \right\rangle \sum_{i=1}^{I} \sum_{j=1}^{I} \left\langle A_i A_j \cos(\phi_{ni} - \phi_{nj} + \psi_i - \psi_j) \right\rangle$$

To continue this analysis we require the joint statistical properties of the phase shifts and the amplitude factors. For our purposes at present we may assume the A_i constant for all i = 1, 2, ...I. But the phase shift properties are needed. Note the following. If $A_i = 1$, all i, and

$$\left\langle \cos(\phi_{ni} - \phi_{nj} + \psi_i - \psi_j) \right\rangle = 0,$$

except when i = j, then

$$\left\langle N^2(t) \right\rangle = I \sum \left\langle n_n^2(t) \right\rangle$$

However, if the angular differences were small so that

$$\left\langle \cos(\phi_{ni} - \phi_{nj} + \psi_i - \psi_j) \right\rangle = 1$$

for all j and j then

$$\left\langle N^2(t) \right\rangle = I^2 \sum \left\langle n_n^2(t) \right\rangle$$

In the latter case the branch noises are correlated and add coherently. In the former case they are uncorrelated and add incoherently.

The difference angle statistics are under investigation and will be reported later. A preliminary calculation indicates that for the array size envisioned in this application the angular differences may be large enough for the first condition above to be approximately correct.

Fred Haber

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-- 11 - TITLE:     (U)  RESEARCH IN DISTRIBUTED ARRAYS
--  1 - AGENCY ACCESSION NO:   DN775290
--  2 - DATE OF SUMMARY: 12 NOV  80
-- 39 - PROCESSING DATE (RANGE):      30 NOV  80
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--                  000200 ACOUSTICS
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--10A2 - PRIMARY PROJECT NUMBER:       F11121
--10A2A - PRIMARY PROJECT AGENCY AND PROGRAM:      F11121
--10A3 - PRIMARY TASK AREA:      RF11121810
--10A4 - WORK UNIT NUMBER:       NR-129-102
--17A1 - CONTRACT/GRANT EFFECTIVE DATE:      MAR 77
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-- 17C - CONTRACT TYPE:    COST TYPE
--17D2 - CONTRACT/GRANT AMOUNT:        $ 25,000
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-- 17F - CONTRACT/GRANT CUMULATIVE DOLLAR TOTAL:     $ 130,000
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-- 20N - PERF. ORGANIZATION TYPE CODE: 1
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-- 23 - TECHNICAL OBJECTIVE: (U) TO DEVELOP TECHNIQUES IN SIGNAL ANALYSIS
-- TO MAXIMIZE ACHIEVABLE ARRAY GAIN OF A RANDOM SONOBUOY ARRAY
-- 24 - APPROACH: (U) INVESTIGATE PHASE DECORRELATION EFFECT ON ARRAY GAIN
-- AND WAYS TO OVERCOME THESE EFFECTS
-- 25 - PROGRESS: (U) EARLIER WORK FOCUSED ON METHODS OF LOCALIZING ELEMENTS
-- OF A RANDOM ARRAY. THEORY HAS BEEN DEVELOPED. VALLEY FORGE RESEARCH
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